J. Astrophys. Astr. (2011) **32,** 257–260

Curvature Effect and the Spectral Softening Phenomenon Detected in GRB Afterglows

Y.-P. Qin
Center for Astrophysics, Guangzhou University, Guangzhou 510006, People's Republic of China.
email: ypqin@gzhu.edu.cn

Abstract. Detection of radiation from a relativistic fireball would be affected by the so-called curvature effect. I illustrate the expected temporal and spectral behaviours of this effect and show that it can well explain the observed spectral softening in the early GRB afterglows.

Key words. Gamma-rays: bursts—gamma-rays: theory—relativity.

1. Introduction

Gamma-ray bursts (GRBs) are astrophysical events of very short duration emitted in high energy bands (gamma-ray bands) from deep space. The events were detected in the 1960s (Klebesadel *et al.* 1973). Great progress has been made in the past few decades, owing to the successful launch of various satellites. Early observations show that GRBs are uniformly distributed on the sky, which strongly supports the cosmological origin scenario (Meegan *et al.* 1992). A great breakthrough emerged in 1997. Afterglows of some GRBs were detected by BeppoSAX satellite, and then redshift measurements of these sources were available, which confirmed that these extreme events are at cosmological distances (Costa *et al.* 1997; Metzger *et al.* 1997; van Paradijs *et al.* 1997; Djorgovski *et al.* 1998).

A steep decay phase was discovered with Swift/XRT in the early X-ray afterglows of some GRBs. It is generally regarded as the tail of the prompt gamma-rays due to the time delay of the photons at high latitude of the fireball. Surprisingly, in the tails of many bursts, clear spectral softening evolution was detected (Campana *et al.* 2006; Gehrels *et al.* 2006; Ghisellini *et al.* 2006; Mangano *et al.* 2007; Zhang *et al.* 2007a). Zhang *et al.* (2007b) performed a systematic analysis on the steep decay segment for a sample of 44 GRBs and found that 33 of them showed clear hard-to-soft spectral evolution, indicating that this spectral softening is not a rare phenomenon in GRBs. I illustrate here that this phenomenon can be explained with the curvature effect only.

2. Fireball hypothesis

It is generally believed that after the original explosion, the event of GRBs will begin to evolve from an expanding fireball (Goodman 1986; Paczynski 1986), and then will create radiation by shocks (Rees & Meszaros 1992, 1994; Meszaros & Rees

1993, 1994; Katz 1994; Paczynski & Xu 1994; Sari *et al.* 1996). This gives rise to the so-called curvature effect that has been accounted for various temporal and spectral properties of GRBs (see e.g., Fenimore *et al.* 1996; Meszaros & Rees 1998; Hailey *et al.* 1999; Kumar & Panaitescu 2000; Qin 2002; Ryde & Petrosian 2002; Kocevski *et al.* 2003; Qin *et al.* 2004).

Several factors influence the curvature effect in distinct aspects. (a) The expanding motion of the fireball influences the time contraction, the Doppler effect factor, the growth of the fireball radius or enhancement of the fireball's surface, and the variation of intensity. (b) The line of sight angle itself affects the time contraction factor, the Doppler effect factor and the variation of intensity. (c) The variation of the line of sight angle along the fireball surface causes time delay of the emission from high latitude areas and the shifting of the intrinsic spectrum. Taking all these into account, the so-called full curvature effect takes place (for detailed explanation and analysis, see Qin 2002, 2008; Qin *et al.* 2004, 2006).

To meet and/or approximate the conventional definition of observation time, t is assigned as (see Qin 2008, 2009)

$$t \equiv t_{\rm ob} - t_{\rm c} + R_{\rm c}/v - D/c, \tag{1}$$

where $t_{\rm c}$ as a time constant is defined in the observer frame, D is the distance of the fireball to the observer, v is the speed of the shell, $R_{\rm c}$ is the radius of the shell measured at $t_{\rm c}$ by local observers who are stationary in the explosion area. With this definition of observation time, basic formulas of the full curvature effect are as follows:

$$\begin{aligned} f_\nu(t) \;=\; & \frac{2\pi c^2}{D^2(\Gamma v/c)^2 t^2}\int_{\widetilde{t}_{0,\min}}^{\widetilde{t}_{0,\max}} I_{0,\nu}(t_0,\nu_0)[R_{\rm c}/c + (t_0 - t_{0,{\rm c}})\Gamma v/c]^2 \\ & \times[(t_0 - t_{0,{\rm c}})\Gamma + R_{\rm c}/v - t]{\rm d}t_0, \end{aligned} \tag{2}$$

with

$$\widetilde{t}_{0,\min} = \max\{t_{0,\min}, \frac{t - R_{\rm c}/v + (R_{\rm c}/c)\cos\theta_{\max}}{[1-(v/c)\cos\theta_{\max}]\Gamma} + t_{0,{\rm c}}\}, \tag{3}$$

$$\widetilde{t}_{0,\max} = \min\{t_{0,\max}, \frac{t - R_{\rm c}/v + (R_{\rm c}/c)\cos\theta_{\min}}{[1-(v/c)\cos\theta_{\min}]\Gamma} + t_{0,{\rm c}}\}, \tag{4}$$

$$\nu_0 = \frac{t}{R_{\rm c}/v + (t_0 - t_{0,{\rm c}})\Gamma}\Gamma\nu \tag{5}$$

and

$$\begin{aligned} & [1-(v/c)\cos\theta_{\min}][(t_{0,\min} - t_{0,{\rm c}})\Gamma + R_{\rm c}/v] \le t \\ & \le [1-(v/c)\cos\theta_{\max}][(t_{0,\max} - t_{0,{\rm c}})\Gamma + R_{\rm c}/v] \end{aligned}, \tag{6}$$

where $t_{0,{\rm c}}$ denotes the moment of $t_{\rm c}$, measured by a co-moving observer; $I_{0,\nu}(t_0,\nu_0)$ is the intrinsic radiation intensity; $\Gamma = 1/\sqrt{1 - v^2/c^2}$. According to equation (1), $t = 0$ corresponds to the moment of the emission that occurs at the spot of the

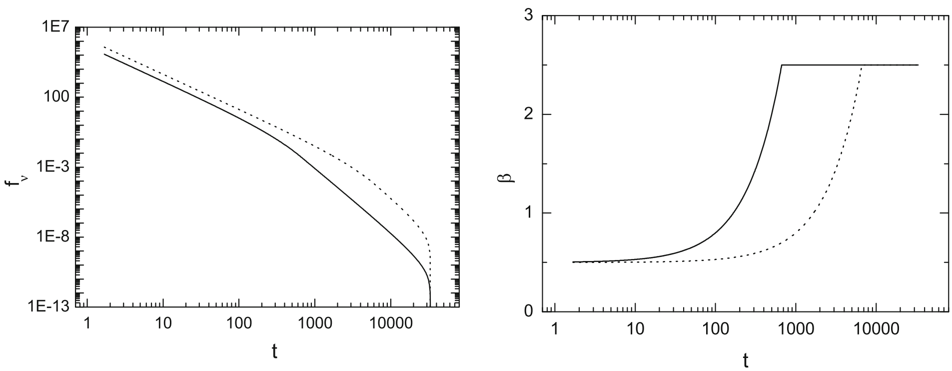

Figure 1. The light curve (the left panel) and spectral evolution (the right panel) of a δ function emission from an expanding fireball, expected at 2 keV (solid lines) and 0.2 keV (dotted lines) observation frequencies respectively. Other parameters are the same as those adopted in Qin (2009).

explosion (i.e., $t = 0$ is the moment when photons emitted from $R_c = 0$ reach the observer).

3. Prediction based on general spectral forms

Concerning a general form of spectrum, several predictions can be made from the above equations (Qin 2009). (a) The same form of spectrum could be observed at different times. (b) The observed spectrum is expected to shift with time (e.g., the peak energy of the band function spectrum would appear at higher energy bands at early times but it would appear at lower energy bands at later times). (c) Within a wide range of time, there exists a temporal steep decay phase accompanied by spectral softening. (d) In most cases, the temporal power law index α and the spectral power law index β will be related by $\alpha = 2 + \beta$. The $\alpha = 2 + \beta$ relation will be broken down and $\alpha > 2 + \beta$ or $\alpha >> 2 + \beta$ will hold at much later time when the latitude of the emission area is very high.

Illustrated in Fig. 1 are the light curve and spectral evolution expected at 2 keV and 0.2 keV observation frequencies, respectively (for the details of the adopted parameters, see Qin 2009). It reveals a spectral softening appearing in the steep decay phase of the light curve at quite an early time of X-ray observation, no matter the observation frequency is at higher bands or at lower bands. In fact, for two GRBs, the spectral softening can be well fitted by the curvature effect when a more general form of spectrum rather than a pure power-law spectrum is considered (Qin 2009; Zhang *et al.* 2009).

4. Conclusions

We conclude as follows.

- It is the shifting of the observed spectrum that causes both the steep decay light curve and spectral softening at an early time of X-ray observation of GRBs.
- The softening phenomenon is nothing but a consequence of the curvature effect.

References

Campana, S. *et al.* 2006, *Nature*, **442**, 1008.
Costa, E. *et al.* 1997, *Nature*, **387**, 783.
Djorgovski, S. G. *et al.* 1998, *Astrophys. J.*, **508**, L17.
Fenimore, E. E., Madras, C. D., Nayakshin, S. 1996, *Astrophys. J.*, **473**, 998.
Gehrels, N. *et al.* 2006, *Nature*, **444**, 1044.
Ghisellini, G. *et al.* 2006, *Mon. Not. R. Astron. Soc.*, **372**, 1699.
Goodman, J. 1986, *Astrophys. J.*, **308**, L47.
Hailey, C. J., Harrison, F. A., Mori, K. 1999, *Astrophys. J.*, **520**, L25.
Katz, J. I. 1994, *Astrophys. J.*, **422**, 248.
Klebesadel, R. W., Strong, I. B., Olson, R. A. 1973, *Astrophys. J.*, **182**, L85.
Kocevski, D., Ryde, F., Liang, E. 2003, *Astrophys. J.*, **596**, 389.
Kumar, P., Panaitescu, A. 2000, *Astrophys. J.*, **541**, L51.
Mangano, V. *et al.* 2007, *Astron. Astrophys.*, **470**, 105.
Meegan, C. A. *et al.* 1992, *Nature*, **355**, 143.
Meszaros, P., Rees, M. J. 1993, *Astrophys. J.*, **405**, 278.
Meszaros, P., Rees, M. J. 1994, *Mon. Not. R. Astron. Soc.*, **269**, L41.
Meszaros, P., Rees, M. J. 1998, *Astrophys. J.*, **502**, L105.
Metzger, M. R. *et al.* 1997, *Nature*, **387**, 878.
Paczynski, B. 1986, *Astrophys. J.*, **308**, L43.
Paczynski, B., Xu, G. 1994, *Astrophys. J.*, **427**, 708.
Qin, Y.-P. 2002, *Astron. Astrophys.*, **396**, 705.
Qin, Y.-P. *et al.* 2004, *Astrophys. J.*, **617**, 439.
Qin, Y.-P. *et al.* 2006, *Phys. Rev.*, **D74**, 063005.
Qin, Y.-P. 2008, *Astrophys. J.*, **683**, 900.
Qin, Y.-P. 2009, *Astrophys. J.*, **691**, 811.
Rees, M. J., Meszaros, P. 1992, *Mon. Not. R. Astron. Soc.*, **258**, 41p.
Rees, M. J., Meszaros, P. 1994, *Astrophys. J.*, **430**, L93.
Ryde, F., Petrosian, V. 2002, *Astrophys. J.*, **578**, 290.
Sari, R., Narayan, R., Piran, T. 1996, *Astrophys. J.*, **473**, 204.
van Paradijs, J. *et al.* 1997, *Nature*, **386**, 686.
Zhang, B. *et al.* 2007a, *Astrophys. J.*, **655**, L25.
Zhang, B.-B. *et al.* 2007b, *Astrophys. J.*, **666**, 1002.
Zhang, B.-B., Zhang, B., Liang, E.-W., Wang, X.-Y. 2009, *Astrophys. J.*, **690**, L10.